Gas Exchange of Apple and Blackberry Leaves Treated with a Kaolin Particle Film on Adaxial, Abaxial, or Both Leaf Surfaces

Jean-Pierre Privé¹, Lindsay Russell, and Anita LeBlanc

Agriculture and Agri-Food Canada, Atlantic Food and Horticulture Research Center, 1045 St. Joseph Road, Bouctouche, N.B. E4S 2J2 Canada

Additional index words. *Malus × sylvestris*, New Brunswick, organic, photosynthesis, *Rubus*

Abstract. Kaolin particle films are used as a means of pest control in some commercial apple orchards in the Maritime provinces; however, no studies to date have evaluated the impact of these particle films on leaf gas exchange under the region's growing conditions. Also previously unexplored is the gas exchange response of blackberry leaves to kaolin particle films and the question of whether leaf gas exchange response varies according to the leaf surface of particle film application. A study consisting of an apple field trial and a blackberry greenhouse trial was conducted during the 2005 growing season in Bouctouche, New Brunswick, Canada, with the aims of 1) characterizing the leaf temperature and gas exchange responses [net photosynthesis, stomatal conductance (g_s), intercellular CO_2 , and transpiration] of 'Ginger Gold' apple [*Malus × sylvestris* (L.) Mill var. *domestica* (Borkh.) Mansf.] leaves to a kaolin particle film (95% kaolin clay) applied at various leaf residue densities under the province's growing conditions, 2) characterizing the leaf temperature and gas exchange responses of 'Triple Crown' blackberry (*Rubus* L. subgenus *Rubus* Watson) leaves to treatment of adaxial or abaxial surfaces with the kaolin particle film at various leaf residue densities, and 3) determining whether the gas exchange response of apple and blackberry leaves to the kaolin particle film varies according to leaf temperature. Leaf gas exchange measurements were taken under conditions of ambient CO_2 , saturated light, moderate (apple) or high (blackberry) relative humidity levels and leaf temperatures ranging from 26 to 39 °C (apple) and 15 to 41 °C (blackberry). When the particle film was applied to both the adaxial and abaxial surfaces of apple leaves at kaolin residue densities of 0.5 to 3.7 g·m⁻², leaf temperature was reduced by up to 1.1 °C ($P = 0.005$) and g_s was increased ($P = 0.029$) relative to leaves with trace (<0.5 g·m⁻²) levels of kaolin deposits. No other effects of kaolin leaf residue density on apple leaf gas exchange were found, nor were any interactions of leaf temperature × residue level ($P > 0.05$). When applied to a fixed area on the adaxial or abaxial surfaces of blackberry leaves at kaolin residue densities of 0.5 to 10.8 g·m⁻², the particle film did not alter leaf temperature or gas exchange ($P > 0.05$). No interactions of leaf temperature × residue level or leaf temperature × leaf surface × residue level were found to affect blackberry leaf gas exchange ($P > 0.05$).

Surround wettable powder (Engelhard Corp.; Iselin, NJ) is a processed kaolin [$Al_4Si_4O_{10}(OH)_8$] clay-based crop protectant approved for use in the organic production of a variety of crops, including apple and blackberry. It was developed for broad-spectrum insect pest control and has other applications including, but not limited to, disease control and protection against heat stress and solar injury (Glenn and Puterka, 2005). The product forms a white, reflective physical barrier called a "particle film" on the plant

surface. Although designed not to interfere with leaf gas exchange, the findings to this end are mixed (Glenn and Puterka, 2005). Differences in product application, climatic conditions, crop or cultivar, and physiological state of the plants may account for some of the disparity between these findings.

A number of past pomological studies have investigated the impact of kaolin particle films on insect pests, disorders and diseases, canopy microclimate and environmental physiology, fruit productivity and quality, and water use efficiency (Glenn and Puterka, 2005). The research pertaining to the use of kaolin particle films in blackberry production is limited to its application as a soil amendment in weed control (Takeda et al., 2005) or to its potential use in frost protection (Agricultural Research Service, 2005).

Some studies indicate that kaolin particle film technology is best suited for use in warm,

arid climates, in which heat stress, not light, is the principal factor limiting production (Erez and Glenn, 2004; Glenn et al., 2003; LeGrange et al., 2004; Schupp et al., 2004). Other findings suggest that particle films favor gas exchange under conditions of environmental (high temperature) and physiological (drought) stress (Glenn et al., 2001). From 'Ginger Gold' [*Malus × sylvestris* (L.) Mill var. *domestica* (Borkh.) Mansf.] leaf gas exchange measurements made in the 2004 season as part of a preliminary study, it appeared that greater rates of net photosynthesis (P_n) were achieved at a higher frequency of kaolin particle film application and that this was particularly the case at leaf temperatures exceeding 35 °C (Privé et al., 2007). Ultraviolet damage and photoinhibition can be additive at plant temperatures exceeding 35 °C (Glenn and Puterka, 2005). Although kaolin particle films are used as a means of pest control in several commercial apple orchards in the Maritime provinces, no previous studies have investigated the effect of these particle films on leaf gas exchange under the region's growing conditions. The New Brunswick growing season is characterized by conditions of low to moderate solar irradiance, moderate temperature, and high humidity. The nature of the physiological response to the kaolin particle film in the region's climate will have a bearing on the use of this product in the Maritime provinces.

No studies to date have investigated the effect of leaf surface (adaxial, abaxial, or both) of kaolin particle film application on leaf gas exchange. Liang and Liu (2002) examined the effect of melon leaf surface treated with a kaolin particle film on oviposition and the repellency of adult silverleaf whiteflies. Abou-Khaled et al. (1970) measured gas exchange of citrus and rubber leaves in the laboratory after having applied a kaolin particle film to the leaves' adaxial surfaces only. Jifon and Syvertsen (2003) observed that grapefruit leaves with their adaxial surface coated with a kaolin particle film had greater light reflectance than those with abaxial surfaces coated (the latter of which had reflectance levels comparable with those of untreated control leaves), and also found that the application of the particle film to both leaf surfaces did not result in an increase in reflectance over that measured for the adaxial surface alone. Most studies pertaining to the effect of kaolin particle films on leaf gas exchange involve field trials in which the kaolin product is applied indiscriminately to all foliage, as it would in a commercial orchard setting, as opposed to selective application of the particle film to individual leaves. In one instance of the former, a greater density of particle deposition on the adaxial surface (6.5 g·m⁻²) than on the abaxial surface (4.8 g·m⁻²) was observed for mature 'Braeburn' apple leaves (Wünsche et al., 2004). It is recommended that both surfaces of the leaf be evenly coated with the particle film to achieve optimal performance (Glenn and Puterka, 2005). It can, however, be difficult in practice to achieve thorough,

Received for publication 15 Dec. 2006. Accepted for publication 23 Feb. 2007.

We are grateful to Kenneth McRae and Bradley Walker for their assistance on the statistical analysis, and to Peter Havard and Daniel Cudmore for engineering the precision sprayer.

¹To whom reprint requests should be addressed; e-mail privej@agr.gc.ca

uniform kaolin particle deposition on all leaves in the canopy using common agricultural spraying equipment, and great variability in kaolin residue densities can frequently be observed not only among leaves, but between the two surfaces of any one leaf. The leaf surface on which the stomata are located varies by plant species. They are located primarily on the abaxial surface of apple and blackberry leaves. Any variation in leaf physiological response related to differences in particle film coverage between leaf surfaces would be of practical consideration in informing the method of product application.

The current study is comprised of a 'Ginger Gold' apple field trial and a 'Triple Crown' (*Rubus* L. subgenus *Rubus* Watson) blackberry greenhouse trial. Both of these fruit cultivars display a number of attributes that make them desirable for production in the Maritime region (Galletta et al., 1998; Privé, 2004). 'Ginger Gold' is a yellow-skinned, early-maturing cultivar. Damage incited by pests, pathogens, and environmental disorders is all the more prominent on 'Ginger Gold' fruit because of its skin color. Not as winter hardy as raspberries, no blackberry cultivars are currently recommended for cultivation in the Maritime provinces; however, interest in blackberry production in the region is growing, and trials are currently underway to evaluate the viability of some of the hardier cultivars. 'Triple Crown' is a thornless, late-summer-ripening blackberry cultivar with a potential for cultivation in the region that is currently being investigated. Results of a 7-year field trial carried out in Oregon indicate that 'Triple Crown' fruit are susceptible to ultraviolet light injury (Galletta et al., 1998). Various studies report that kaolin particle films are effective in protecting foliage and fruit from solar injury (Glenn et al., 2002; Melgarejo et al., 2004; Wand et al., 2006). The aims of the current study are 1) to characterize the leaf temperature and gas exchange responses [Pn, stomatal conductance (g_s), intercellular CO_2 (Ci), and transpiration (E)] of 'Ginger Gold' apple [*Malus $\times$ sylvestris* (L.) Mill var. *domestica* (Borkh.) Mansf.] leaves to a kaolin particle film (95% kaolin clay) applied at various leaf residue densities under New Brunswick growing conditions, 2) to characterize the leaf temperature and gas exchange responses of 'Triple Crown' blackberry (*Rubus* L. subgenus *Rubus* Watson) leaves to treatment of abaxial or adaxial surfaces with the kaolin particle film at various leaf residue densities, and 3) to determine whether the gas exchange response of apple and blackberry leaves to the kaolin particle film varies according to leaf temperature.

Materials and Methods

Plant material and experimental treatments. This study, comprised of an apple field trial and a blackberry greenhouse trial, was conducted at Agriculture and Agri-Food Canada's Atlantic Food and Horticulture

Research Center, in Bouctouche, New Brunswick, Canada (lat. 46°26'N, long. 64°46'W). The apple field trial was carried out during the 2005 growing season in a bearing 0.05-ha organic 'Ginger Gold'/'Budagovsky 9' block of the experimental orchard. The block consisted of 60 trees planted in 1995 in five rows (east-west orientation) at 2.5 $\times$ 3.5-m spacing, and was managed in accordance with Nova Scotia provincial organic guidelines (Braun, 2004). The orchard was drip irrigated as necessary, and was not under drought stress. Beginning at full pink, a 5% (w/v) aqueous suspension of Surround wettable powder was applied to the orchard (indiscriminately to both adaxial and abaxial surfaces of foliage) on six occasions between 4 June and 4 Sept., using a commercial air-blast sprayer at a rate of 50 kg-ha⁻¹.

Also carried out in 2005 was a greenhouse blackberry trial. A total of seven 1-year-old 'Triple Crown' (*Rubus* L. subgenus *Rubus* Watson) potted blackberry plants (thinned to two to three primocanes per pot) were used in the study. Plants were fertilized with a 200 μ mol-mol⁻¹ solution of 20N-20P-20K once or twice daily using a drip irrigation system. The light level was supplemented with high-pressure sodium lighting for photoperiods of 16 h to provide saturated light conditions necessary for plant growth and gas exchange measurements. Temperature and light conditions in the greenhouse were regulated using a reflective curtain and overhead fans.

A variable number of healthy, fully expanded leaves with surface areas greater than 11.0 cm² were selected from each tree or plant for leaf gas exchange measurements. In the case of the apple trial, these were mature shoot leaves from the lower to middle range of the outer canopy. As it had been determined in a previous study of raspberry plants that gas exchange properties do not vary with leaf position on the primocane (Privé et al., 1997), recently expanded leaves all along the length of the primocanes of the blackberry plants were selected for measurement. All treatments were represented on each of the blackberry plants.

One application of aqueous Surround suspension 2.5% or 5% (w/v) was made to the adaxial or abaxial surfaces of the selected blackberry leaves, using an ultralow-volume precision sprayer equipped with a 0.7-mm-diameter solid-cone nozzle (Nova Scotia Agricultural College, Bible Hill, Nova Scotia, Canada) that was custom designed for spraying individual leaves; untreated leaves served as Controls. The suspension was applied to leaves to near drip; the sprayer produced a 20.4-cm² solid, circular spray pattern on the leaf surface. In the case of leaves with adaxial and abaxial surfaces that were both treated with the particle film, application was such that the treated areas coincided.

Leaf gas exchange. Leaf temperature and gas exchange (Pn, g_s , Ci, and E) measurements of single, attached leaves (247 apple, 234 blackberry) were performed using a LI-6200 Portable Photosynthesis System equip-

ped with a 0.25-L leaf chamber (LI-COR, Lincoln, NE) per the method described by Privé et al. (1997). Measurements were taken to alternate between leaves with different kaolin residue levels (apple) or between leaves with different leaf surface-residue level combinations (blackberry). In the instance of the kaolin-treated blackberry leaves, gas exchange of the treated areas was measured. Measurements of apple leaves were taken 2 to 12 d after kaolin particle film application on nine occasions preharvest between 8 Aug. and 8 Sept., between the hours of 10:00 and 12:00 AM and 2:00 and 5:00 PM (Atlantic Standard Time). Measurements of blackberry leaves were taken up to 24 h after particle film application on eight occasions between 9 and 30 Sept., between the hours of 8:30 AM and 12:00 PM and 2:00 and 5:30 PM (Atlantic Standard Time). Gas exchange was not measured for leaves from all apple trees in the orchard. All measurements were taken under ambient CO_2 and a minimum of 1000 μ mol-m⁻²-s⁻¹ of photosynthetic photon flux (PPF). It has been reported that apple and blackberry leaves are light saturated at a PPF more than 700 and 1000 μ mol-m⁻²-s⁻¹ respectively (Rom and Clark, 1991; Tartachnyk and Blanke, 2004). Air temperature in the field ranged from 18 to 30 °C during gas exchange measurements. Air flow through the system was adjusted as necessary during measurements to maintain relatively stable readings of vapor pressure deficit.

Kaolin leaf residues. Apple and blackberry leaves were excised after gas exchange measurement. The surface area of apple leaves was measured using a LI-3100 area meter (LI-COR). The quantity of kaolin residues on each leaf was subsequently determined per the extraction method of Knight et al. (2000), which was modified for use on an individual leaf basis, and kaolin leaf residues were reported as densities (mass of residues per unit leaf surface area treated). In the case of the apple leaves, for which the adaxial and abaxial surfaces were both treated with the particle film, kaolin residues were extracted from the entire leaf. In the case of the blackberry leaves, for which only a fixed area of one (20.4 cm²) or both (40.8 cm²) leaf surfaces was treated, the kaolin residues from the treated areas were extracted. Based on the level of their kaolin residues, apple leaves were classified into one of three categories: trace, <0.5 g-m⁻²; low, 0.5 to 2 g-m⁻²; or high, $\geq$ 2 g-m⁻². According to the leaf surface of particle film application and the level of their kaolin residues, blackberry leaves were assigned to one of 10 groupings: untreated control, 0 g-m⁻²; adaxial low, 0.5 to 2 g-m⁻²; adaxial moderate, 2 to 5 g-m⁻²; adaxial high, >5 g-m⁻²; abaxial low; abaxial moderate; abaxial high; adaxial + abaxial low; adaxial + abaxial moderate; and adaxial + abaxial high.

Statistical analysis. Stomatal conductance data in the apple data set were normalized using a square root transformation ($Y = \sqrt{x}$); Pn and g_s data in the blackberry data set

were normalized using a square root ($Y = \sqrt{x}$) and a logarithmic ($Y = \log x$) transformation respectively. Data with residuals that had absolute values greater than three were removed from the data set as outliers.

A mixed-model analysis of the apple data set was performed using the Residual Maximum Likelihood (REML) procedure to determine whether kaolin leaf residue density (trace, $<0.5 \text{ g}\cdot\text{m}^{-2}$; low, $0.5\text{--}2 \text{ g}\cdot\text{m}^{-2}$; high, $>2 \text{ g}\cdot\text{m}^{-2}$), leaf temperature ($<30^\circ\text{C}$, $30\text{--}35^\circ\text{C}$, $\geq 35^\circ\text{C}$), or their interaction had an effect on leaf gas exchange (P_n , g_s , C_i , and E), and whether kaolin residue density had an influence on leaf temperature. Leaf temperature categories were designated based on considerations of the physiological response of apple leaves to temperature (Glenn and Puterka, 2005; Lakso, 1994), in addition to observations made by others (Glenn et al., 2001) and ourselves regarding a differential gas exchange response to kaolin particle films at high and moderate temperatures. The model accounted for the random effects of sampling date, tree sampling period combinations within dates, and leaves within the tree sampling period combinations.

A mixed-model analysis of the blackberry data set was performed using the REML procedure to determine whether leaf temperature ($15\text{--}25^\circ\text{C}$, $>30^\circ\text{C}$), leaf surface (adaxial, abaxial, both, neither), kaolin leaf residue density (control, $0 \text{ g}\cdot\text{m}^{-2}$; low, $0.5\text{--}2 \text{ g}\cdot\text{m}^{-2}$; moderate, $2\text{--}5 \text{ g}\cdot\text{m}^{-2}$; and high, $>5 \text{ g}\cdot\text{m}^{-2}$), or their interactions had an effect on leaf gas exchange (P_n , g_s , C_i , and E), and whether leaf surface, kaolin residue density, or their interaction had an influence on leaf temperature. Kaolin residue categories were similar to those used in the apple analysis, with the addition of a fourth category ($\geq 5 \text{ g}\cdot\text{m}^{-2}$). This level was selected because leaf residues above this density may interfere with leaf gas exchange as a result of shading (Erez and Glenn, 2004). Leaf temperature categories were designated based on the distribution of the data (no observations fell within the 25 to

30°C leaf temperature range) and on considerations of the physiological response of raspberry leaves to temperature (Percival et al., 1996). The model accounted for the random effects of sampling date, leaf surface-kaolin residue combinations within dates, and leaves within the surface-residue combinations.

All statistical analyses were performed using GenStat Release 8.2 statistical software (VSN International Ltd., Herts, UK) at a significance level of 5%, and all figures were plotted using SigmaPlot version 7.1 software (Systat Software, Point Richmond, CA). Means and their ses are reported. Only the results pertaining to the effects of kaolin residue level (apple) and leaf surface $\times$ residue level (blackberry) on leaf temperature and leaf gas exchange are discussed. Interactions of leaf temperature $\times$ residue level (apple, blackberry) and leaf temperature $\times$ leaf surface $\times$ residue level (blackberry) are also reported for leaf gas exchange.

Results and Discussion

The density of kaolin deposits on 'Ginger Gold' apple leaves ranged between 0 and $3.7 \text{ g}\cdot\text{m}^{-2}$ (Fig. 1A). Glenn et al. (2003) reported kaolin residue densities of 3 to $5 \text{ g}\cdot\text{m}^{-2}$ for 'Empire' apple leaves, to which applications of 3% or 6% (w/v) kaolin solution were made weekly for 6 weeks after petal fall and then biweekly until harvest using an air-blast sprayer. Wünsche et al. (2004) reported kaolin residue densities of 4.8 to $6.5 \text{ g}\cdot\text{m}^{-2}$ for 'Braeburn' apple leaves that had been treated once with a 5% kaolin solution applied by a single-nozzle handgun sprayer. Variability, among studies, in the densities of kaolin leaf residues achieved may be ascribed to differences in kaolin product formulation, concentration, frequency, and method of application; time interval between application and measurement; atmospheric conditions (wind, precipitation) to which treated leaves are exposed; or the method used in quantifying residues.

Greater rates of apple leaf P_n and g_s were obtained in the current study (Table 1) than have been reported under comparable field conditions ($5\text{--}17 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ for P_n ; $0.1\text{--}0.8 \text{ mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ for g_s) by others (Glenn et al., 2001; Le Grange et al., 2004). Leaves used for measurement in the current study were light saturated and presumed to be at their maximum photosynthetic rates.

Apple leaf temperatures ranged between 26 and 39°C (Fig. 1A). Leaf temperature decreased with increasing levels of kaolin leaf residues, but remained above the optimum ($25\text{--}30^\circ\text{C}$) for gas exchange of apple leaves (Glenn and Puterka, 2005; Lakso, 1994). At kaolin residue densities of 0.5 to $3.7 \text{ g}\cdot\text{m}^{-2}$, leaf temperature was reduced by up to 1.1°C relative to leaves with trace ($<0.5 \text{ g}\cdot\text{m}^{-2}$) levels of kaolin deposits ($SE = 0.25^\circ\text{C}$; $P = 0.005$; Fig. 2). Wünsche et al. (2004) found an average reduction of 3.1°C in the temperature of kaolin-treated apple leaves (residue densities of up to $6.5 \text{ g}\cdot\text{m}^{-2}$) relative to that of untreated control leaves.

Stomatal conductance increased with increasing levels of kaolin leaf residues. Rates of g_s were 0.880 (transformed) and $0.774 \text{ mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ (back-transformed) for leaves with trace levels of kaolin residues, 0.902 (transformed) and $0.814 \text{ mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ (back-transformed) for leaves with low residue levels, and 0.934 (transformed) and $0.872 \text{ mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ (back-transformed) for leaves with high residue levels [SE (transformed means) = 0.018 ; $P = 0.029$]. By increasing the reflection of infrared and ultraviolet light from treated plant surfaces, the kaolin particle film is said to reduce heat load on the leaf, thereby favoring g_s , and consequently P_n and E (Glenn et al., 2001, 2003). The kaolin-attributed reduction in leaf temperature and attendant increase in g_s did not prove sufficient to alter P_n , C_i , or E (data not shown; $P > 0.05$) under the conditions of the current study. Wünsche et al. (2004) reported that the application of a kaolin particle film to 'Braeburn' apple leaves at

Fig. 1. Temperature of 'Ginger Gold' apple (A) and 'Triple Crown' blackberry (B) leaves as a function of kaolin leaf residue density.

Table 1. Gas exchange of 'Ginger Gold' apple leaves with trace ($< 0.5 \text{ g}\cdot\text{m}^{-2}$), low ($0.5\text{--}2 \text{ g}\cdot\text{m}^{-2}$), and high ($\geq 2 \text{ g}\cdot\text{m}^{-2}$) densities of kaolin residues, as measured at leaf temperatures of $\leq 30^\circ\text{C}$, $30\text{ to }35^\circ\text{C}$, and $\geq 35^\circ\text{C}$.

Leaf temperature ($^\circ\text{C}$)	Pn ($\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$)			g_s ($\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$)			Ci ($\mu\text{mol}\cdot\text{mol}^{-1}$)			E ($\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$)		
	Trace	Low	High	Trace	Low	High	Trace	Low	High	Trace	Low	High
≤ 30	19.3	21.8	23.8	0.956 ^a (0.914)	0.972 (0.945)	1.00 (1.00)	319	315	310	16.1	15.8	16.2
30–35	20.4	21.5	20.8	0.903 (0.815)	0.941 (0.885)	0.922 (0.850)	302	305	310	18.6	19.3	18.4
≥ 35	19.1	18.5	17.9	0.783 (0.613)	0.793 (0.629)	0.879 (0.773)	289	291	300	17.6	18.2	18.7
SE ^b		1.2			0.032			5.1			0.75	
P ^c		0.41			0.41			0.47			0.70	

^aTransformed means reported for g_s ($Y = \sqrt{x}$), with back-transformed means in parentheses.

^bSE = SE of means (where transformed means also reported, SE = SE of transformed means).

^cP is the probability value for interaction of leaf temperature $\times$ residue level; 5% significance level.

Ci, intercellular CO_2 ; E = transpiration; g_s , stomatal conductance; Pn, net photosynthesis.

Fig. 2. Temperature of 'Ginger Gold' apple leaves with trace ($< 0.5 \text{ g}\cdot\text{m}^{-2}$), low ($0.5\text{--}2 \text{ g}\cdot\text{m}^{-2}$), and high ($\geq 2 \text{ g}\cdot\text{m}^{-2}$) levels of kaolin residues.

residue densities of up to $6.5 \text{ g}\cdot\text{m}^{-2}$ resulted in increased light reflectance and reduced leaf temperature. Leaf g_s and E were unaffected, but leaf carbon assimilation was reduced at light levels below saturation because light absorption by leaves at this level of particle film coverage was reduced as a result of the increased reflectance. As in the current study, air temperatures (ranging from $18\text{--}30^\circ\text{C}$) were not high enough to induce extreme heat stress; but, unlike in the current study, light conditions were not always saturated. Moreover, kaolin leaf residues and presumably reflectance were higher and mean leaf temperatures ($24.2\text{--}27.3^\circ\text{C}$) were optimal and much lower than those in the current study. Glenn et al. (2001, 2003) examined the physiological response of leaves of assorted apple cultivars in various geographical locations to treatment with hydrophilic or hydrophobic kaolin particle films (leaf residue densities of $1\text{--}10 \text{ g}\cdot\text{m}^{-2}$) and reported that effects on gas exchange were not observed at air temperatures less than 25°C and where drought or heat stress was not a factor. But under conditions of high ambient temperature (exceeding 30°C), treated trees exhibited reduced leaf temperatures and increased rates of leaf g_s , Pn, and E. Thomas et al. (2004) also observed greater rates of g_s , Pn, and E in kaolin-treated apple leaves of various cultivars, but only under conditions of heat stress with temperatures of $34\text{ to }39^\circ\text{C}$. In a preliminary study, application of a kaolin particle film to apple leaves had a positive effect on rates of g_s , Pn, and E, particularly at leaf temperatures more than 35°C (Privé et al., 2007). However, no interaction of leaf temperature $\times$ residue level

was found in the current study ($P > 0.05$; Table 1).

The density of kaolin residues on treated 'Triple Crown' blackberry leaves ranged between 0.5 and $10.8 \text{ g}\cdot\text{m}^{-2}$ (Fig. 1B). Of the leaves with adaxial surfaces treated with the particle film, the majority had low ($0.5\text{--}2 \text{ g}\cdot\text{m}^{-2}$) kaolin residue densities and none had high ($> 5 \text{ g}\cdot\text{m}^{-2}$) residue densities. Conversely, the majority of the leaves with abaxial surfaces treated with the particle film had high kaolin residue densities. This differential in kaolin residues between treated leaf surfaces can be attributed to differences between the adaxial and abaxial leaf surfaces. The suspension adhered much more readily to the trichomes of the underside of the leaf than to the waxy cuticle of the upper surface of the leaf, from which more product was lost as a result of runoff.

Andersen (1991) characterized blackberry leaves as having intermediate to high rates of Pn and g_s , with rates of $12.1 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ and $0.26 \text{ mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$, respectively, measured for field-grown 'Shawnee' plants under conditions of light saturation. Rotundo et al. (1998) measured Pn and g_s rates of $8.2\text{ to }8.9 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ and $0.14\text{ to }0.16 \text{ mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$, respectively, for leaves of field-grown 'Black Satin' and 'Smoothstem' blackberry plants under full sunlight conditions. Stafne et al. (2001) measured Pn and g_s rates of $8.9\text{ to }11.4 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ and $0.20\text{ to }0.21 \text{ mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$, respectively, for 'Arapaho' blackberry leaves in a growth chamber under light-saturating conditions and air temperatures of $20\text{ to }35^\circ\text{C}$. The somewhat higher rates of leaf Pn and g_s observed in the current study (Table 2) can be explained by the optimal growth conditions (fertigation, saturated light, and high relative humidity) provided by the greenhouse and by the fact that the leaves of the plants were newly expanded at the time of measurement, and were likely at a peak level of photosynthetic activity.

Blackberry leaf temperatures ranged between 15 and 41°C (Fig. 1B). Kaolin particle film application (leaf surface $\times$ residue level) was not found to affect leaf temperature (data not shown; $P > 0.05$). Because the particle film was only applied to a fixed area on one (20.4 cm^2) or both (40.8 cm^2) surfaces of the blackberry leaves, rather than to the entire leaf surface, and because the untreated areas of the treated leaves would not have reflected much irradiance, this partial coverage of the leaf surface with the

particle film, even at the higher residue densities, may not have been sufficient to mitigate heat load and thus leaf temperature.

This reduction in heat load is said to be the mechanism underlying the action of kaolin particle films on gas exchange (Glenn and Puterka, 2005). Because no reduction in the temperature of kaolin-treated blackberry leaves was observed, it is not surprising that no effect of particle film application (kaolin leaf surface $\times$ residue level) on leaf gas exchange was found ($P > 0.05$; Table 2). As a result of differences in the adherence of the particle film to the upper and lower leaf surfaces, no adaxial-treated leaves with high levels of kaolin residues and abaxial-treated leaves with low amounts of residues were represented in the analysis. Moreover, the occurrence of both kaolin-treated and untreated areas on the surface of treated blackberry leaves may have been a confounding factor. Irrespective of kaolin leaf residue level, effects of the particle film on leaf temperature and gas exchange may only be realized when the entire leaf surface is treated. In an apple field study, Glenn et al. (2001) found that the carbon assimilation of leaves treated with a hydrophobic kaolin particle film (residue densities of $1\text{--}5 \text{ g}\cdot\text{m}^{-2}$) did not differ from that of untreated leaves when trees were adequately irrigated and temperatures did not exceed 25°C . Lombardini et al. (2005) suggested that kaolin particle films may not benefit carbon assimilation under conditions of adequate irrigation. The plants in the current study did not exhibit signs of physiological stress. They were well irrigated and growing under conditions of high relative humidity (90% to 100%), with mean leaf temperatures near the optimum (25°C) for carbon exchange of blackberry leaves (Stafne et al., 2001). No interactions of leaf temperature $\times$ residue level ($P > 0.05$; Table 3) or leaf temperature $\times$ leaf surface $\times$ residue level (data not shown; $P > 0.05$) were found in the blackberry trial.

To avoid any diurnal effects on leaf physiology, such as a midday depression in Pn, gas exchange measurements of apple and blackberry leaves were not made during the midday hours, which are characterized by conditions of high irradiance and temperature. Jifon and Syvertsen (2003) found that the application of a particle film to grapefruit leaves led to a 30% reduction in midday photoinhibition. Glenn et al. (2001) observed less of an afternoon depression in Pn of

Table 2. Gas exchange of 'Triple Crown' blackberry leaves with low (<2 g·m⁻²), moderate (2–5 g·m⁻²), high (>5 g·m⁻²), and no (untreated control) kaolin residues on adaxial or abaxial leaf surfaces.

Treated surface	Pn (μmol·m ⁻² ·s ⁻¹)			g _s (mol·m ⁻² ·s ⁻¹)			Ci (μmol·mol ⁻¹)			E (mol·m ⁻² ·s ⁻¹)		
	Control	Low	Moderate	High	Control	Low	Moderate	High	Control	Low	Moderate	High
Untreated	3.62 ^z (13.1)	NA	NA	NA	-0.332 (0.466)	NA	NA	NA	333 (9.02)	NA	NA	NA
Adaxial	NA	3.71 (13.7)	3.39 (11.5)	—	NA	-0.351 (0.445)	-0.384 (0.413)	—	NA	2.88 (8.32)	2.81 (7.90)	—
Abaxial	NA	—	3.70 (13.7)	3.78 (14.3)	NA	—	-0.336 (0.462)	-0.308 (0.492)	NA	—	3.06 (9.37)	3.14 (9.86)
Adaxial + Abaxial	NA	3.69 (13.6)	3.63 (13.2)	3.76 (14.2)	NA	-0.369 (0.428)	-0.347 (0.450)	-0.321 (0.478)	NA	2.90 (8.44)	2.97 (8.82)	3.05 (9.30)
SE ^y		0.15				0.039				0.072		
P ^x		0.53				0.94				0.38		

^zTransformed means reported for Pn (Y = √x), g_s (Y = log x), and E (Y = √x), with back-transformed means in parentheses.

^ySE = SE of means (where transformed means also reported, SE = SE of transformed means).

^xP is the probability value for interaction of leaf surface × residue level; 5% significance level.

Ci, intercellular CO₂; E = transpiration; g_s, stomatal conductance; NA, not applicable (surfaces of control leaves not treated with kaolin particle film); Pn, net photosynthesis; —, no data available.

Table 3. Gas exchange of 'Triple Crown' blackberry leaves with low (<2 g·m⁻²), moderate (2–5 g·m⁻²), high (>5 g·m⁻²), and no (untreated control) kaolin residues as measured at leaf temperatures of ≤25 °C and ≥30 °C.

Leaf temperature (°C)	Pn (μmol·m ⁻² ·s ⁻¹)			g _s (mol·m ⁻² ·s ⁻¹)			Ci (μmol·mol ⁻¹)			E (mol·m ⁻² ·s ⁻¹)		
	Control	Low	Moderate	High	Control	Low	Moderate	High	Control	Low	Moderate	High
≤25	3.29 ^z (10.8)	3.08 (9.49)	3.09 (9.55)	3.08 (9.49)	-0.399 (0.399)	-0.538 (0.290)	-0.472 (0.337)	-0.420 (0.380)	351 (2.00)	1.74 (3.03)	1.89 (3.57)	1.96 (3.84)
≥30	3.95 (15.6)	4.24 (18.0)	4.06 (16.5)	4.46 (19.9)	-0.264 (0.545)	-0.199 (0.632)	-0.239 (0.577)	-0.208 (0.619)	306 (4.01)	4.00 (16.1)	4.01 (16.1)	4.23 (17.9)
SE ^y		0.21				0.054				0.098		
P ^x		0.36				0.20				0.39		

^zTransformed means reported for Pn (Y = √x), g_s (Y = log x), and E (Y = √x), with back-transformed means in parentheses.

^ySE = SE of means (where transformed means reported, SE = SE of transformed means).

^xP is probability value for interaction of leaf temperature × residue level; 5% significance level.

Ci, intercellular CO₂; E, transpiration; g_s, stomatal conductance; Pn, net photosynthesis.

kaolin-treated apple leaves. It may be that in the current study, similar results were achieved with the kaolin particle film during the midday hours, but went unobserved.

In summary, when applied as a coating to the foliage of 'Ginger Gold' apple trees at leaf residue densities of 0.5 to 3.7 g·m⁻², a kaolin particle film was found to reduce leaf temperature and favor g_s under New Brunswick field conditions, when light was not a limiting factor. When applied to a fixed area of the adaxial or abaxial surfaces of 'Triple Crown' blackberry leaves at residue densities of 0.5 to 10.8 g·m⁻², the kaolin particle film did not affect leaf temperature or gas exchange under optimal greenhouse conditions, regardless of residue density and leaf surface of application. For both apple and blackberry leaves, gas exchange response to kaolin particle film did not vary according to leaf temperature. It would appear that the use of kaolin particle film technology in New Brunswick apple orchards can reduce the heat load and favor the gas exchange of apple leaves. Such benefits would possibly be all the more marked under conditions of physiological stress. It remains to be seen whether the application of a kaolin particle film to the entire leaf surface, which is more representative of the practice in a commercial setting, affects the temperature and gas exchange of blackberry leaves.

Literature Cited

- Abou-Khaled, A., R.M. Hagan, and D.C. Davenport. 1970. Effects of kaolinite as a reflective antitranspirant on leaf temperature, transpiration, photosynthesis, and water-use efficiency. *Water Resource Res.* 6:280–289.
- Agricultural Research Service, U.S. Department of Agriculture. 2005. Research. 13 Dec. 2005. <http://www.ars.usda.gov/research/projects/projects.htm?ACCN_NO=408394>.
- Andersen, P.C. 1991. Leaf gas exchange of 11 species of fruit crops with reference to sun-tracking–non-sun-tracking responses. *Can. J. Plant Sci.* 71:1183–1194.
- Braun, P.G. (ed.). 2004. Organic apple production guide for Nova Scotia. Organic Agr. Ctr. Can., Truro, NS, Canada.
- Erez, A. and D.M. Glenn. 2004. The effect of particle-film technology on yield and fruit quality. *Acta Hort.* 636:505–508.
- Galletta, G.J., J.L. Maas, J.R. Clark, and C.E. Finn. 1998. 'Triple Crown' thornless blackberry. *Fruit Var. J.* 52:124–127.
- Glenn, D.M., A. Erez, G.J. Puterka, and P. Gundrum. 2003. Particle films affect carbon assimilation and yield in 'Empire' apple. *J. Amer. Soc. Hort. Sci.* 128:356–362.
- Glenn, D.M., E. Prado, A. Erez, J. McFerson, and G.J. Puterka. 2002. A reflective, processed-kaolin particle film affects fruit temperature, radiation reflection, and solar injury in apple. *J. Amer. Soc. Hort. Sci.* 127:188–193.
- Glenn, D.M. and G.J. Puterka. 2005. Particle films: A new technology for agriculture. *Hort. Rev.* (Amer. Soc. Hort. Sci.) 31:1–44.
- Glenn, D.M., G.J. Puterka, S.R. Drake, T.R. Unruh, A.L. Knight, P. Baherle, E. Prado, and A. Baugher. 2001. Particle film application influences apple leaf physiology, fruit yield, and fruit quality. *J. Amer. Soc. Hort. Sci.* 126:175–181.

- Jifon, J.L. and J.P. Syvertsen. 2003. Kaolin particle film applications can increase photosynthesis and water use efficiency of 'Ruby Red' grapefruit leaves. *J. Amer. Soc. Hort. Sci.* 128: 107–112.
- Knight, A.L., T.R. Unruh, B.A. Christianson, G.J. Puterka, and D.M. Glenn. 2000. Effect of a kaolin-based particle film on obliquebanded leafroller (Lepidoptera: Tortricidae). *J. Econ. Entomol.* 93:744–749.
- Lakso, A.N. 1994. Apple, p. 3–42. In: B. Schaffer and P.C. Andersen (eds.). *Handbook of environmental physiology of fruit crops*. Vol. 1: Temperate crops. CRC Press, Boca Raton, FL.
- LeGrange, M., S.J.E. Wand, and K.I. Theron. 2004. Effect of kaolin applications on fruit quality and gas exchange of apple leaves. *Acta Hort.* 636:545–550.
- Liang, G. and T.X. Liu. 2002. Repellency of a kaolin particle film, Surround, and a mineral oil, sunspray oil, to silverleaf whitefly (Homoptera: Aleyrodidae) on melon in the laboratory. *J. Econ. Entomol.* 95:317–324.
- Lombardini, L., M.K. Harris, and D.M. Glenn. 2005. Effects of particle film application on leaf gas exchange, water relations, nut yield, and insect populations in mature pecan trees. *HortScience* 40:1376–1380.
- Melgarejo, P., J.J. Martínez, F.C.A. Hernández, R. Martínez Font, P. Barrows, and A. Erez. 2004. Kaolin treatment to reduce pomegranate sunburn. *Sci. Hort.* 100:349–353.
- Percival, D.C., J.T.A. Proctor, and M.J. Tsujita. 1996. Whole-plant net CO₂ exchange of raspberry as influenced by air and root-zone temperature, CO₂ concentration, irradiation, and humidity. *J. Amer. Soc. Hort. Sci.* 121:838–845.
- Privé, J.P. 2004. Rootstock affects performance of 'Ginger Gold' apple trees. *Agriculture and Agri-Food Canada technical report no 04–1*.
- Privé, J.P., L. Russell, G. Braun, and A. LeBlanc. 2007. 'Bordeaux'/'Kumulus' regimes and 'Surround' in organic apple production in New Brunswick: Impacts on apple scab, fruit russetting and leaf gas exchange. *Acta Hort.* 737:95–104.
- Privé, J.P., J.A. Sullivan, and J.T.A. Proctor. 1997. Seasonal changes in net carbon exchange rates of Autumn Bliss, a primocane-fruiting red raspberry (*Rubus idaeus* L.). *Can. J. Plant Sci.* 77:427–431.
- Rom, C.R. and J.R. Clark. 1991. Gas exchange characteristics of field-grown 'Shawnee' blackberry. *HortScience* 26:71–72 (abstr.).
- Rotundo, A., M. Forlani, and C. Di Vaio. 1998. Influence of shading net on vegetative and productive characteristics, gas exchange and chlorophyll content of the leaves in two blackberry (*Rubus ulmifolius* Schott.) cultivars. *Acta Hort.* 457:333–340.
- Schupp, J.R., E. Fallahi, and I.J. Chun. 2004. Effect of particle film on fruit sunburn, maturity and quality of 'Fuji' and 'Honeycrisp' apples. *Acta Hort.* 636:551–556.
- Stafne, E.T., J.C. Clark, and C.R. Rom. 2001. Leaf gas exchange response of 'Arapaho' blackberry and six red raspberry cultivars to moderate and high temperatures. *HortScience* 36:880–883.
- Takeda, F., D.M. Glenn, and T. Tworkoski. 2005. Weed control with hydrophobic and hydrous kaolin clay particle mulches. *HortScience* 40:714–719.
- Tartachnyk, I.I. and M.M. Blanke. 2004. Effect of delayed fruit harvest on photosynthesis, transpiration and nutrient remobilization of apple leaves. *New Phytol.* 164:441–450.
- Thomas, A.L., M.E. Miller, B.R. Dodson, M.R. Ellersieck, and M. Kaps. 2004. A kaolin-based particle film suppresses certain insect and fungal pests while reducing heat stress in apples. *J. Amer. Pomol. Soc.* 58:42–51.
- Wand, S.J.E., K. Theron, J. Ackerman, and S.J.S. Marais. 2006. Harvest and post-harvest apple fruit quality following applications of kaolin particle film in South African orchards. *Sci. Hort.* 107:271–276.
- Wünsche, J.N., L. Lombardini, and D.H. Greer. 2004. 'Surround' particle film applications: Effect on whole canopy physiology of apple. *Acta Hort.* 636:565–571.